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# BULGELESS GALAXIES AND THEIR ANGULAR MOMENTUM PROBLEM

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## ABSTRACT

The specific angular momentum of Cold Dark Matter (CDM) halos in a ΛCDM universe is investigated. Their dimensionless specific angular momentum $\lambda' = \frac{j}{\sqrt{2}V_{vir}Rvir}$ with $V_{vir}$ and $R_{vir}$ the virial velocity and virial radius, respectively depends strongly on their merging histories. We investigate a set of ΛCDM simulations and explore the specific angular momentum content of halos formed through various merging histories. Halos with a quiet merging history, dominated by minor mergers and accretion until the present epoch, acquire by tidal torques on average only 2% to 3% of the angular momentum required for their rotational support ($\lambda' = 0.02$). This is in conflict with observational data for a sample of late-type bulgeless galaxies which indicates that those galaxies reside in dark halos with exceptionally high values of $\lambda' \approx 0.06 - 0.07$. Minor mergers and accretion preserve or slowly increase the specific angular momentum of dark halos with time. This mechanism is however not efficient enough in order to explain the observed spin values for late-type dwarf galaxies. Energetic feedback processes have been invoked to solve the problem that gas loses a large fraction of its specific angular momentum during infall. Under the assumption that dark halos hosting bulgeless galaxies acquire their mass via quiescent accretion, our results indicate yet another serious problem: the specific angular momentum gained during the formation of these objects is not large enough to explain their observed rotational properties, even if no angular momentum would be lost during gas infall.

*Subject headings:* cosmology: theory – galaxies: formation

## 1. INTRODUCTION

The dynamical structure of disc galaxies is dominated by angular momentum. Therefore, understanding the origin of angular momentum in these systems is crucial in any theory of galaxy formation. In the current paradigm for structure formation, dark matter is assumed to be cold and collisionless and luminous galaxies form by gas infall into dark matter halos, which grow by gravitational accretion and merging in a hierarchical fashion (White & Reese 1978). Fall & Efstathiou (1980, hereafter FE80) proposed that the sizes of galactic disks are linked to the angular momentum of their parent dark matter halos. This theory is able to produce disks with sizes that are in agreement with observations, if the gas initially had the same specific angular momentum as dark matter halos show today and if the gas preserved its specific angular momentum during the protogalactic collapse phase. The angular momentum of galaxies results from torques due to tidal interactions with neighbouring structures, acquired early, before the halo decoupled from the Hubble expansion.

Many models for the formation of galactic disks have been proposed, based on the picture of FE80. Most of them incorporate the mass accretion history of halos and are able to reproduce many properties of observed disk galaxies (e.g. Mo, Mao & White 1998; Firmani & Avila-Reese 2000; van den Bosch 2000). However, in these models, the angular momentum of the dark matter halos is assigned without accounting for their merging history. Recent results from numerical N-body simulations have pointed out that the effect of major mergers is to increase the mean angular momentum content of the halos (Gardner 2001, G01 hereafter; Vitvitska et al. 2001). This is explained by the orbital angular momentum of the merging halos which dominates the final net angular momentum of the remnant (G01). However, numerical simulations that incorporate gas dynamics have difficulties to make realistic disk galaxies in the current cosmological paradigm. In most simulations, the disks are smaller, denser and have much lower angular momenta than observed disk systems. Simulations show that galaxies are built up by merging of baryonic subclumps, rather than smooth accretion of gas. Most of the gas cools at the centre of subhalos and spirals toward the center of the parent halo, transferring orbital angular momentum to the surrounding dark matter (e.g. Navarro & Steinmetz 2000). More acceptable fits to real disk systems can be found if heuristic prescriptions of stellar feedback are included in the simulations (Sommer-Larsen et al. 2003; Abadi et al. 2003, Robertson et al. 2004). However, even in these simulations the disk systems typically contain denser and more massive bulges than observed in late-type galaxies.

Most of the previous work has focused on angular momentum properties of halos that had at least one dominant major merger during their evolution. In this Letter we explore the angular momentum properties of halos that did not experience any major merger since redshift 3 and that are in principle good candidates to host bulgeless galaxies. We demonstrate that even these galaxies have an angular momentum problem that is directly related with the spin of their dark halos and cannot be solved easily by energetic feedback processes.

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## 2. SIMULATIONS

We performed three simulations within a $\Lambda$CDM cosmological universe with $\Omega_0 = 0.3$, $\Omega_\Lambda$=0.7, $h$=H$_0$/70 km s$^{-1}$ Mpc$^{-1}$ and $\sigma_8 = 0.9$. The simulated volume was 15 $h^{-1}$ Mpc box size in all runs. Each simulation was performed using the publicly available version of the smoothed particle hydrodynamics (SPH) code GADGET (Springel, Yoshida & White 2001). All runs started at redshifts sufficiently high to ensure that the absolute maximum density contrast $|\delta| \leq 1$. The simulations began from a spatially uniform grid of $128^3$ equal-mass particles with Plummer–equivalent softening comoving length of $10h^{-1}$ kpc. The particle masses was $1.34 \times 10^8$ $h^{-1}$ M$_\odot$.

We identify halos with the classic friend-of-friend (FOF) method using a linking length that corresponds to the mean interparticle separation at that density contour that defines the virial radius of an isothermal sphere, $b = [n\rho_{vir}(z)/ < \rho(z) > /3.0]^{-1/3}$=0.15, where $n$ is the particle number density and $\rho_{vir}(z)$ is the corresponding virial density. All halos at z=0 with masses between M= $10^{11} - 10^{12}$ $h^{-1}$ M$_\odot$, containing at least 1000 particles are included in the analyses. This restriction limits the influence of numerical effects on global halo properties. Disks with non-negligible bulge components of $B/(B + D) \geq 0.1$, with B and D the bulge and disk mass, respectively, require a major merger which involved at least 10% of their final mass (i.e. at least 100 particles). Our focus on halos with final particle numbers of at least 1000 therefore guarantees that we don't miss any relevant major merger events due to softening. We also did not find a dependence of our results on the adopted mass range of dark halos at $z = 0$. Therefore, neglecting smaller halos will not affect our conclusions.

## 3. BULGE TO DISK RATIO VS. SPIN PARAMETER

The angular momentum of a galaxy, $J$, is commonly expressed in terms of the dimensionless spin parameter $\lambda = J\sqrt{|E|}$/GM$^{5/3}$where $E$ is the total energy, and M is the total mass. The halo spin parameter distribution in simulations is found to be well approximated by the log-normal function:

$$p(\lambda)\mathrm{d}\lambda = \frac{1}{\sigma_\lambda\sqrt{2\pi}}\exp\Big[-\frac{\ln^2(\lambda/<\lambda>)}{2\sigma_\lambda^2}\Big]\frac{\mathrm{d}\lambda}{\lambda} \qquad (1)$$

In practise, it is more convenient to use the modified spin parameter (Bullock et al. 2001): $\lambda' = j/(\sqrt{2}V_{vir}R_{vir})$ where $j = J/M$ is the specific angular momentum. For a $\Lambda$CDM cosmology the log-normal parameters are found to be $<\lambda'>= 0.035 \pm 0.006$ and $\sigma_{\lambda'}$=0.5-0.6 (Bullock et al. 2001).

We trace each identified halo backward in time, following the mass of the most massive progenitor as a function of redshift during $0 < z < 3$. Our results don't change if we include major mergers at higher redshifts since they in general don't include a last mass fraction. In addition, the gas content of halos with such a high redshift is probably large and the result of a major merger is very unclear (Bullock et al. 2001). We start when the mass of the most massive progenitor is 30% of the z=0 mass. Assuming instead 50% of the halo mass at present time does not change the results. To identify mergers, we denote a halo as a major merger remnant if at some time during $0 < z < 3$ its major progenitor was classified as a single group in one output, but two separate groups with a mass ratio$\leq 4 : 1$ in the preceeding output. The critical mass ratio of 4:1 for a major merger event is based on results of N-body simulations which show that at least such a mass ratio is required in order to produce a spheroidal elliptical galaxy with a surface density profile that agrees with observations of early-type galaxies (Burkert & Naab 2003, BN03 hereafter). We find that 1:1 and 2:1 mergers are much more frequent than 3:1 or 4:1 mergers, in agreement with earlier results by Khochfar & Burkert (2004), based on an analyses of a much larger cube. As discussed earlier, we expecte our identified halo population to be complete at z=0 for masses $\geq 10^{11}$ M$_\odot$. A slight incompleteness for 4:1 mergers right at this mass limit is expected which should however not affect our results, as 4:1 mergers in this limited mass range are very rare. For each halo we identify the time of the last major merger. We assume that accretion events and minor mergers encrease the mass of the disk component whereas major mergers convert all the available gas into stars and destroy disks, forming a stellar spheroid (BN03). Neglecting galactic winds and assuming a universal baryon fraction for all infalling substructures, the final ratio between bulge mass B and the sum of bulge and disk mass (B+D) is given by the ratio of the dark halo mass at the time of the last major merger, divided by the dark halo mass at $z = 0$.

Fig.1 shows the B/(B+D) ratio at z=0 of halos analysed in one of our simulations as a function of their spin parameter $\lambda'$. For better visualisation we just plot the results of one run as the other two runs show similar trends. Different symbols are used to denote halos that have their last major merger at different epochs (see legend in Fig.1). The plot shows that the halo spin parameter is a function of the ratio between bulge mass and total baryonic mass. Many halos with high B/(B+D) ratios also show higher $\lambda'$ values than the average $<\lambda'>\approx 0.035$ in the log-normal distribution (filled symbols in Fig.1). Most of these halos experienced a recent major merger in the redshift range $0 < z < 1$. Halos that have not experienced any major mergers from 0$< z < 3$, show a log-normal distribution with $<\lambda'>\approx 0.023$, significantly lower than the value of 0.035 corresponding to the average referred to all halos. This finding confirms previous results that the last major merger event is affecting the final halo spin parameter distribution (G01; Vitvitska et al. 2002, Peirani et al. 2002). In order to test how reasonable is to set to zero in Fig.1 the bulge masses of halos that have not experienced any major merger from 0$< z < 3$, we traced back the "quiescient" halos, attributing bulge masses different from zero to those halos with the last major merger occurs before z=3. They show bulge mass B between 1%-7% of the sum of bulge and disk mass (B+D). Since we are interested in bulgeless galaxies, we focus here on halos with a quiet merging history dominated by minor mergers and accretion which corresponds to roughly 10% of all halos. It would be interesting to compare the theoretically predicted frequency of bulgeless galaxies with observations. This would however require a much larger survey with higher resolution and larger box sizes which we postpone to a subsequent paper.

In the general picture of FE80, disks should have the

same distribution of total specific angular momentum as the dark matter halos, with the same value for the spin parameter, $\lambda'_{disk} \approx \lambda'$. This is expected because all the material experiences the same external torques during the early expansion phase before separating into two distinct components as a result of dissipative processes during the collapse phase. Numerical simulations have shown that gas and dark matter have identical angular momentum distributions after the protogalactic collapse if cooling is ignored (van den Bosch et al. 2002). During the protogalactic collapse phase, if cooling is included, baryons lose most of their initial angular momentum to the dark matter by dynamical friction (Navarro & Steimetz 2000), resulting in galactic disks that are smaller than observed. Suppression of early cooling of the gas by energetic heating e.g. through supernovae is invoked as a mechanism to prevent this angular momentum catastrophe. We find however that disk-dominated late-type galaxies inhabiting halos that have not experienced a major merger have a distribution of $\lambda'_{disk}$ that peaks around a value of 0.023 which is substantially smaller than expected from observed rotation curves. To demonstrate that we use the results of van den Bosch, Burkert & Swaters (2001, BBS hereafter) who determined spin parameters for galactic disks of 14 late-type bulgeless dwarf galaxies. Fig.1 shows the spin parameters of their galaxies, assuming a mass-to-light ratio of unity in the R band. The result is surprising: none of our models lies in the region of the diagram covered by the observational data.

Fig.2 (top panel) shows the probability distribution of the spin parameter of halos that did not experience any major mergers since z=3 (dashed region) and compares it with the normalized probability distribution of $\lambda'_{disk}$ for the sample of galaxies measured by BBS. The dwarf galaxies show a distribution that follows a log-normal with an average value for $\lambda'_{disk} \approx 0.067$, and a dispersion of $\sigma_{\lambda'} \approx 0.31$. This is a factor of 3 larger than predicted by the numerical simulations. Again, galactic disks would be too small. It is remarkable that multiplying the $\lambda'$ values of simulated halos by a factor 3.15 (dotted histogram in Fig.2) reproduces the peak and dispersion of the observed $\lambda'_{disk}$ distribution quite well. Thus, the discrepancy could be due to a systematic underestimation by a factor of 3 of the product $R_{vir} \cdot V_{vir}$ in the BBS sample. However, if $R_{vir} \cdot V_{vir}$ is increased of a factor of 3, then $M_{vir}$ increases of a factor of $3^{1.5} \approx 5.2$, which implies a factor 5 smaller baryon fraction. The inferred baryon fraction in the BBS sample is already quite small (see Fig.3 of BBS). This solution therefore appears to be very unlikely. On the other hand, the dispersion $\sigma_{\lambda'}$ derived from the observations is in good agreement with the dispersion 0.36, derived for disk galaxies, based on an analysis of 1000 Sb-Sdm galaxies (de Jong & Lacey 2000). In the bottom panel of Fig.2 we show the probability distribution of the spin parameter of the entire halo population (thin solid line). The distribution is a log-normal with $\lambda'_0 = 0.034 \pm 0.005$ and a width $\sigma = 0.45 \pm 0.03$. The value for $\sigma$ is somewhat smaller than previous analysis (G01; Bullock et al. 2001). It is however still within the statistical uncertainties that will in future work be reduced by analysing larger cubes. The figure also shows the frequency of Sub-populations are also included in the total halo histogram showing the result if major merger are defined as mergers with mass ratios $> 1:4$ (thick solid line), $> 1:3$ (dotted line) and $> 1:2$ (long-dashed line), respectively. Note that the spin distributions of the late-type dwarfs in the bottom panel of Fig.2 is in disagreement with all theoretical distributions. Another point of concern could be a dependence of rotational properties on galaxy mass. In our simulations all analysed halos have masses between M= $10^{11} - 10^{12}$ $h^{-1}$ $M_\odot$ which is a factor of 10 to 100 larger than the inferred virial mass of the observed dwarf galaxies of the BBS sample. One might argue that halos of lower mass have higher spin parameters, although it is well known that the spin parameter distribution of halos is independent of mass (Lemson & Kauffmann 1999). We have investigated this question and find no correlation between $\lambda'$ and $M_{vir}$ of the quiet halos in our simulations.

## 4. DISCUSSION AND CONCLUSION

If bulgeless galaxies have not experienced any major mergers during their evolution our analysis shows that their dark halos are characterized by systematically lower angular momentum than observed. Halos without major mergers acquire their specific angular momentum through tidal torques in the early epochs of evolution (Barnes & Efsthatiou 1987), when the density contrasts were small, in accordance with the prediction of the linear theory. In Fig.3, top panel, the spin parameter evolution of the major progenitors of two representative halos is shown. Due to the lack of any major merger event, there is no sharp increase in $\lambda'$ which is characteristic for major mergers. Instead, $\lambda'$ is almost constant and slightly increasing with time, proving that minor mergers and accretion does not affect or significantly decrease $\lambda'$, in contradiction with claims of Vitvitska et al. 2002. The bottom panel shows that the halos aggregate mass gradually by accretion of small subhalos. Robertson et al. (2004) have recently presented the results of a cosmological hydrodynamic simulation where they form an extended, bulge-less disk galaxy. In our sample of "quiescent" halos, there is one case with high spin value ($\lambda' = 0.05$ at z=0), increasing more than a factor of 2 from z=0 and z=3 and no major merger during that time. In its accretion history, mergers with mass ratio 1:5, 1:6 seem to be enough to spin up the halo, although they are unlikely in CDM scenario. Thus, of course this object could be a good candidate to be a bulgeless galaxies and we are resimulating it with higher resolution (D'Onghia et al. in preparation), but cannot be considered as a representative "quiescient" halo. Robertson et al. 2004 could have simulated an object with similar properties, although the authors don't report the spin parameter value or the accretion history of their object.

The net result seems to be that tidal torques generate halos with typical spin parameters of $\lambda' = 0.02$ whereas data for bulgeless galaxies indicate halos with values of $\lambda' = 0.06 - 0.07$. One might worry that our result is affected by the adopted small cosmological volume of 15 $h^{-1}$ Mpc box size, that might suppress torques by by larger-scale structures. However tidal forces scale as $F \propto 1/r^3$. Compared to the forces that are generated by structures at a Mpc distance, structures located at distances of 10 Mpc need to have the mass $10^3$ larger than at 1 Mpc to have the same effect on protogalaxies. At 100 Mpc, the mass

of the structure would have to be even$10^6$ times larger to torque protogalaxies efficiently, which is unlikely. In addition, our results are in agreement with the models of G01 for a larger volume of 100 Mpc box size.

At the moment it is not at all clear how one can reconcile the observations and theory. It is known that the spin parameter distribution for the collapsed objetcs is insensitive to the shape of the initial power spectrum of density fluctuations, to the environment and the adopted cosmological model (Lemson & Kauffmann 1999). A modification of the nature of dark matter does not seem to solve the problem either. Recent works show that warm dark matter halos have systematically smaller spins than their counterparts in ΛCDM (Knebe et al. 2002; Bullock, Kravtsov & Colin 2002), although in this scenario the presence of pancakes could provide more efficient torques on the protohalos. Feedback was invoked as a mechanism to prevent the process of drastic angular momentum loss of infalling gas. (BBS; Maller, Dekel & Somerville 2002). However, we have shown here that the dark halos that experienced no major mergers have already too low an angular momentum to produce the observed disks and no feedback process is know that would increase the the specific angular momentum of the gas. The origin of extended bulgeless disk galaxies remains a puzzle.

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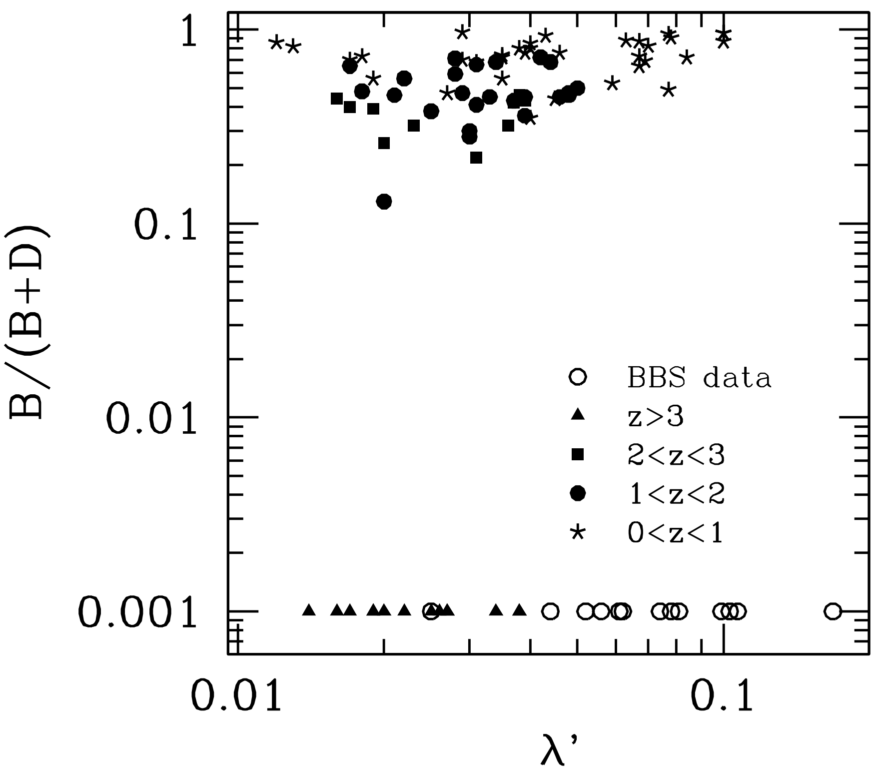


FIG. 1.— The bulge mass (B) compared to the total baryonic mass (B+D) is plotted for each halo against its spin parameter computed at z=0. Different symbols mark halos that had the last major merger at different epochs. The spin parameter values measured for 14 late-type dwarf galaxies by van den Bosch, Burkert & Swaters (2001)(BBS) are also plotted.

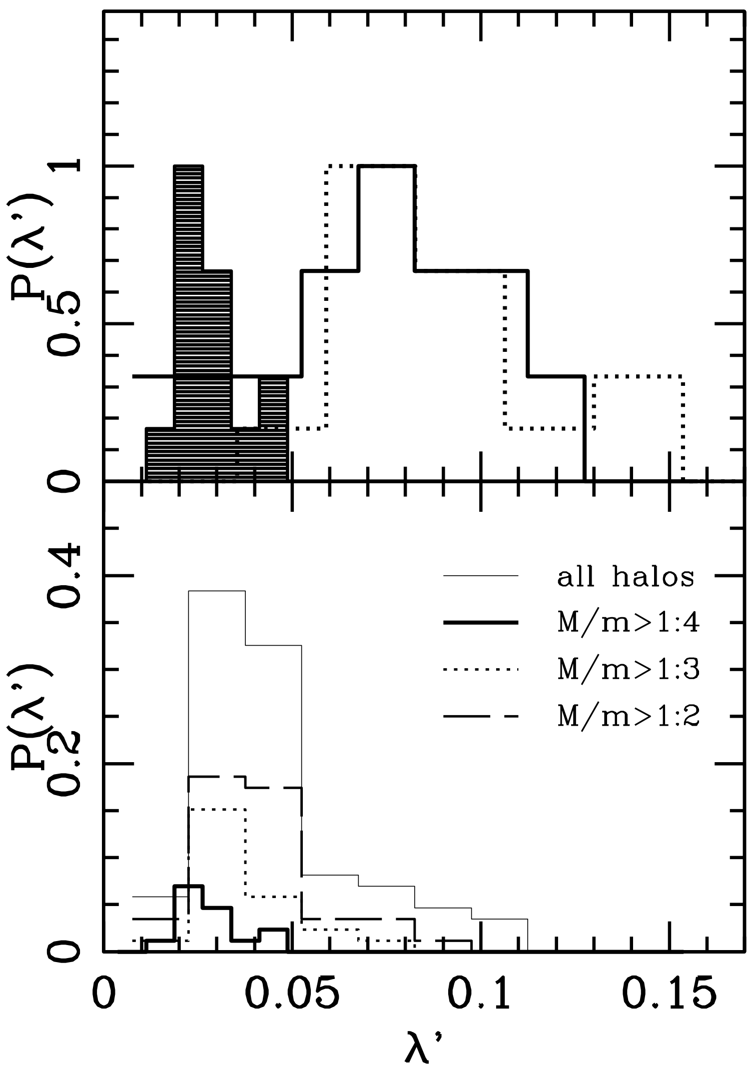


FIG. 2.— *Top Panel.* The probability distribution of the spin parameter of halos that did not experience any major merger since z=3 (dashed region) is compared to the distribution inferred from the BBS data (solid line). The dotted line shows the result if the $\lambda'$-values of the simulated halo distribution would be multiplied by a factor of 3.15. *Bottom Panel.* The probability distribution of the spin parameter of the entire halo population (thin solid line). Sub-populations are also plotted if one assumes that the definition of a major mergers requires mass ratios of $> 1:4$, $> 1:3$, and $> 1:2$, respectively, since z=3.

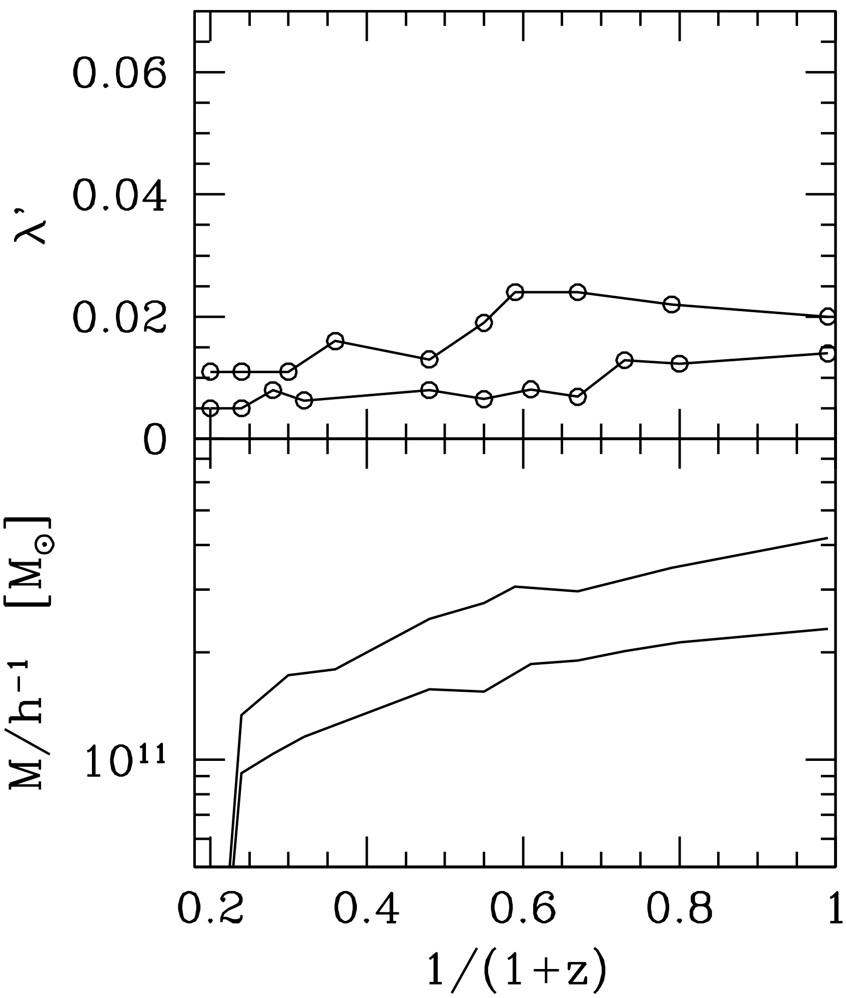


FIG. 3.— The spin parameter evolution of the major progenitors of two representative halos that did not experience any major merging since z=3 (top panel) and their corresponding mass accretion history (bottom panel) is shown.